

The launching condition of a jet driven by the magnetic field and radiation pressure of an accretion disc

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ABSTRACT

We find that the cold gas can be magnetically launched from the disc surface with the help of the radiation pressure if the angular velocity of the radiation pressure dominated accretion disc is greater than a critical value, which decreases with increasing the disc thickness H_d/R (radiation pressure). This indicates the force exerted by the radiation from the disc indeed helps launching the outflow. The rotational velocity of the gas in the disc depends on the strength of the magnetic field threading the disc and the inclination κ_0 ($\kappa_0 = B_z/B_r$) of the field line at the disc surface. The launching condition for the cold gas at the disc surface sets an upper limit on the magnetic field strength, which is a function of the field line inclination κ_0 and the disc thickness H_d/R . This implies a more strict constraint on the maximal jet power can be extracted from a radiation pressure dominated accretion disc than that derived conventionally on the equipartition assumption.

Key words: (galaxies:) quasars: general—accretion, accretion discs—black hole physics—galaxies: jets—magnetic fields

1 INTRODUCTION

The winds driven from the accretion disc through the magnetic field lines threading the disc have been considered as promising explanations for jets/outflows observed in different types of the sources, such as, active galactic nuclei (AGNs), X-ray binaries, and young stellar objects (see reviews in Spruit 1996; Konigl & Pudritz 2000; Pudritz et al. 2007; Spruit 2010). In this model, the ordered magnetic field co-rotates with the gases in the disc, and a small fraction of the gases are driven along the field line by the centrifugal force (Blandford & Payne 1982). The jets are powered by the rotational kinetic energy of the disc through the ordered field threading the accretion disc in this scenario. A crucial ingredient of this model is the angle of the field line inclined to the midplane of the disc being less than $\sim 60^\circ$ is required for launching jets from the midplane of the Keplerian cold disc (Blandford & Payne 1982). This critical angle could be larger than 60° for the accretion disc surrounding a rapidly spinning black hole (Cao 1997), which indicates that the spin of black hole may help launching jets centrifugally by cold magnetized discs (Cao 1997; Sądowski & Sikora 2010). Such analyses were carried out based on two assumptions, the gas is cold (i.e., without considering its internal energy), and the gas is initially launched from the midplane of a Keplerian accretion disc. Strictly speaking, the circular motion of the gases in the accretion disc always deviates from Keplerian motion in the presence of a large-scale magnetic field, which usually exerts a radial force against the gravitation of the central object, and the accretion disc threaded by ordered magnetic field lines is therefore always sub-Keplerian

(Ogilvie & Livio 1998, 2001; Cao & Spruit 2002; Cao 2011). The gases are dominantly accelerated by the centrifugal force, which is proportional to $R\Omega(R_i)$ (R_i is the radius of the magnetic field line footpoint, and Ω is the angular velocity of the accretion disc). A strong magnetic field is helpful for launching the gases, while the stronger field leads to a lower circular velocity of the gas in the disc, which decreases the mass loss rate in the outflow or even suppresses the outflow. Such effects on the launch of the outflow have been extensively explored in the previous works (e.g., Ogilvie & Livio 1998, 2001; Cao & Spruit 2002).

It was also suggested that the outflow can be accelerated by the radiation pressure of the disc (e.g., Shlosman, Vitello, & Shaviv 1985; Murray et al. 1995). Proga (2000) performed numerical simulations on the radiation-driven winds from a luminous Keplerian accretion disc threaded by a strong large-scale ordered magnetic field. It is found that the radiation force is essential in producing winds from the disc if the thermal energy of the gas is low or the field lines make an angle of greater than 60° with respect to the disc midplane. The numerical simulations carried out in Proga (2000) are limited to the Keplerian accretion discs. Recently, the global structure of the accretion discs and outflows around black holes was investigated with radiation-magnetohydrodynamic simulations (e.g., Takeuchi, Ohsuga, & Mineshige 2010; Ohsuga & Mineshige 2011). Similar investigations were carried out for the cases of massive young stars by Vaidya et al. (2011). It is found that the magnetic force, together with the radiation force exerted by accretion discs, can efficiently drive outflows from luminous accretion discs.

It is believed that the black holes are accreting at high rates in

narrow-line Seyfert I galaxies (NLS1s), some young radio galaxies, and microquasars (e.g., Sulentic et al. 2000; Czerny et al. 2009; Wu 2009; Fender, Belloni, & Gallo 2004). Most of NLS1s are radio-quiet, while a fraction of them are radio-loud and some of them may possess relativistic jets (e.g., Zhou et al. 2003; Doi et al. 2006; Yuan et al. 2008; Gu & Chen 2010). For microquasars, for example, GRS 1915+105, relativistic jets are present in their high-luminosity states (e.g., see Fender, Belloni, & Gallo 2004). The outflows/jets in these sources accreting at high rates may probably be magnetically launched from the radiation pressure-dominated accretion discs.

In this work, we explore the condition for cold gas driven by the magnetic force and the radiation force from the surface of a radiation pressure dominated accretion disc. The disc structure, especially the circular motion velocity of the gases in the disc, is altered in the presence of a strong large-scale ordered magnetic field threading the disc, which is properly considered in this work. We describe our analyses in Sections 2 and 3, and the results and discussion are in Sections 4 and 5.

2 STRUCTURE OF AN RADIATION PRESSURE DOMINATED ACCRETION DISC

The accretion disc is assumed to be hydrodynamical equilibrium in the vertical direction. For the gas pressure-dominated accretion disc, the gradient of the gas pressure is balanced with the gravity and magnetic force due to the curvature of the field in the vertical direction (Ogilvie & Livio 1998, 2001; Cao & Spruit 2002; Cao 2011). However, the situation is slightly different for the radiation pressure-dominated accretion disc, the vertical component of gravitational force of the black hole is balanced with the radiation pressure of the disc and the vertical component of the magnetic force at the disc surface $z = H_d$ (Laor & Netzer 1989). The curvature of the field line at the disc surface is usually very small, and the vertical component of the magnetic force can be neglected in the estimate of the disc scale-height. The scale-height of the disc can be estimated with

$$\frac{GMH_d}{(R_i^2 + H_d^2)^{3/2}} = \frac{f_{\text{rad}}\kappa_T}{c}, \quad (1)$$

which can be re-written as

$$\frac{\tilde{H}_d}{(1 + \tilde{H}_d^2)^{3/2}} = \frac{f_{\text{rad}}\kappa_T}{R_i\Omega_K^2 c}, \quad (2)$$

where f_{rad} is the flux from the unit surface area of the disc, $\tilde{H}_d = H_d/R_i$, and $\Omega_K = (GM/R_i^3)^{1/2}$ is the Keplerian angular velocity at R_i .

In a geometrically thin accretion disc, the circular velocity is almost Keplerian without magnetic fields. The circular motion of the disc becomes sub-Keplerian in the presence of magnetic fields, and the angular velocity Ω of the disc can be calculated with

$$R_i\Omega_K^2 - R_i\Omega^2 = \frac{B_R^S B_z}{2\pi\Sigma_d R_i} = \frac{B_z^2}{2\pi\Sigma_d R_i\kappa_0}, \quad (3)$$

where Σ_d is the surface density of the disc, B_R^S and B_z are the radial and vertical components of the field at the disc surface $z = H_d$ respectively, and $\kappa_0 = B_z/B_R^S$. The radial gradient of radiation pressure in the disc is not included in Equation (3), which is negligible compared with the magnetic force in the thin accretion disc if the magnetic field is sufficient strong.

The pressure of a radiation pressure dominated accretion disc at the mid-plane is

$$p_d = \frac{4\sigma}{3c} T_c^4, \quad (4)$$

where T_c is the central temperature of the disc. The flux radiated from the unit area of the disc surface is given by

$$f_{\text{rad}} = \frac{8\sigma T_c^4}{3\Sigma_d\kappa_T}. \quad (5)$$

Equation (4) can therefore be re-written as

$$p_d = \frac{\Sigma_d\kappa_T f_{\text{rad}}}{2c}. \quad (6)$$

Substituting Equations (2), (4), and (5) into Equation (3), we have

$$1 - \tilde{\Omega}^2 = \frac{2\beta\tilde{H}_d}{\kappa_0(1 + \tilde{H}_d^2)^{3/2}}, \quad (7)$$

where the dimensionless quantities $\tilde{\Omega}$, and β , are defined as

$$\tilde{\Omega} = \frac{\Omega}{\Omega_K}; \quad \beta = \frac{B_z^2}{8\pi} / p_d. \quad (8)$$

3 LAUNCHING CONDITION FOR COLD GAS FROM THE DISC SURFACE

The condition for the cold gas can be launched from the mid-plane of a Keplerian accretion disc was given in Blandford & Payne (1982), which is a good approximation for geometrically thin accretion discs with weak magnetic fields, i.e., the rotation of the discs has not been altered much by the field. The situation becomes complicated for the gas driven from the surface of a real disc with finite thickness in the presence of a strong magnetic field. In this case, the rotation of the gas in the disc deviates significantly from the Keplerian value (see discussion in Section 2).

The effective potential along the field line threading the accretion disc with angular velocity Ω at radius R_i is

$$\Psi_{\text{eff}}(R, z) = -\frac{GM}{(R^2 + z^2)^{1/2}} - \frac{1}{2}\Omega(R_i)^2 R^2, \quad (9)$$

without considering the radiation force exerted on the gas in the outflow. It becomes

$$\Psi_{\text{eff}}(R, z) = -\frac{GM}{(R^2 + z^2)^{1/2}} - \frac{1}{2}\Omega(R_i)^2 R^2 - \frac{f_{\text{rad}}}{c}\kappa_T z, \quad (10)$$

while the radiation pressure is considered, where f_{rad} is the flux emitted from the unit surface area of the disc, and the Thompson scattering cross-section $\kappa_T = 0.4 \text{ g}^{-1} \text{ cm}^{-2}$. For the outflow from the inner region of the disc, the gases are almost completely ionized and the Thompson scattering cross-section is therefore a good approximation. The analysis carried out in this work can be applied to the outflow driven by the radiation pressure due to the line absorption if the Thompson scattering cross-section is replaced by the line opacity, though line driven outflows are usually from the outer region of the disc (e.g., Shlosman, Vitello, & Shaviv 1985; Murray et al. 1995; Proga, Stone, & Kallman 2000).

Substituting Equation (2) into Equation (10), the effective potential along the field line threading the accretion disc with angular velocity Ω at radius R_i can be re-written in dimensionless form,

$$\begin{aligned} \tilde{\Psi}_{\text{eff}}(r, \tilde{z}) &= \frac{\Psi_{\text{eff}}(R, z)}{R_i^2\Omega_K^2} \\ &= -\frac{1}{(r^2 + \tilde{z}^2)^{1/2}} - \frac{1}{2}\tilde{\Omega}^2 r^2 - \frac{\tilde{z}\tilde{H}_d}{(1 + \tilde{H}_d^2)^{3/2}}, \end{aligned} \quad (11)$$

where $r = R/R_i$, and $\tilde{z} = z/R_i$. Differentiating Equation (11), we have

$$\frac{d\tilde{\Psi}_{\text{eff}}(r, \tilde{z})}{dr} = \frac{r + \tilde{z}\kappa_0}{(r^2 + \tilde{z}^2)^{3/2}} - r\tilde{\Omega}^2 - \frac{\tilde{H}_d\kappa_0}{(1 + \tilde{H}_d^2)^{3/2}}, \quad (12)$$

which reduces to

$$\left. \frac{d\tilde{\Psi}_{\text{eff}}(r, \tilde{z})}{dr} \right|_{r=1, \tilde{z}=\tilde{H}_d} = \frac{1}{(1 + \tilde{H}_d^2)^{3/2}} - \tilde{\Omega}^2, \quad (13)$$

at the disc surface, $r = 1$ and $\tilde{z} = \tilde{H}_d$. This means that the cold gas can be magnetically launched from the disc surface with the help of radiation pressure only if the condition,

$$\left. \frac{d\tilde{\Psi}_{\text{eff}}(r, \tilde{z})}{dr} \right|_{r=1, \tilde{z}=\tilde{H}_d} \leq 0, \quad (14)$$

is satisfied, which requires

$$\tilde{\Omega} \geq \frac{1}{(1 + \tilde{H}_d^2)^{3/4}}. \quad (15)$$

Substituting Equation (7) into Equation (15), the condition becomes

$$\beta \leq \frac{\kappa_0}{2\tilde{H}_d} [(1 + \tilde{H}_d^2)^{3/2} - 1], \quad (16)$$

for the cold gas being able to leave the disc surface along the field line. In order to clarify the role of the radiation force in launching the jets/outflows, we analyze two special cases: A $f_{\text{rad}} \rightarrow 0$ and $\tilde{\Omega} \rightarrow 1$; and, B f_{rad} is not considered and $\tilde{\Omega} < 1$.

3.1 Case A: $f_{\text{rad}} \rightarrow 0$ and $\Omega/\Omega_K \rightarrow 1$

In our model, the circular velocity of the accretion discs deviates from the Keplerian value in the presence of magnetic fields. A lower β leads to a larger angular velocity $\tilde{\Omega}$ for a fixed value of κ_0 (see Equation 7), which helps launching the outflow. The results derived here are different from that derived in Blandford & Payne (1982) for the gas driven from the midplane of a Keplerian disc. One may expect that our calculation can reproduce the Blandford-Payne's result on the critical angle of the field line with respect to the disc plane, below which the cold gas can be launched from the mid-plane of a Keplerian disc. For a radiation pressure dominated accretion disc, the gravity of the black hole is balanced with the radiation pressure of the disc in the vertical direction, which means that the disc thickness $H_d \rightarrow 0$ in the limit of $f_{\text{rad}} \rightarrow 0$ (see Equation 2), and $\tilde{\Omega} \rightarrow 1$ is automatically satisfied (see Equation 7). Thus, our model calculation corresponds to the case considered in Blandford & Payne (1982) for the cold gas from the mid-plane of a Keplerian disc in the limit of $\tilde{H}_d \rightarrow 0$. We find that $d\tilde{\Psi}_{\text{eff}}(r, \tilde{z})/dr = 0$ if $\tilde{H}_d = 0$ (see Equation 13). It implies that the gas can always be in equilibrium independent of the field line inclination κ_0 . This is the same as that in Blandford & Payne (1982). Therefore, one has to calculate the second derivative of the effective potential to check the stability of equilibrium,

$$\frac{d^2\tilde{\Psi}_{\text{eff}}(r, \tilde{z})}{dr^2} = \frac{-2r^2 - 6r\tilde{z}\kappa_0 - 2\tilde{z}^2\kappa_0^2 + \tilde{z}^2 + r^2\kappa_0^2}{(r^2 + \tilde{z}^2)^{5/2}} - \tilde{\Omega}^2, \quad (17)$$

which is required to be negative at $r = 1$ and $\tilde{z} = \tilde{H}_d = 0$ for the cold gas can be launched from the midplane of the disc. This leads to

$$\kappa_0 < \kappa_{0,\text{crit}} = \sqrt{3}, \quad (18)$$

which reaches the same result given in Blandford & Payne (1982). Our calculations show that gas at the disc surface is not in equilibrium state when the angular velocity is greater than a critical value for the disc with finite thickness, and therefore the launch condition for the cold gas at the disc surface can be derived by the first derivative of the effective potential $d\tilde{\Psi}_{\text{eff}}(r, \tilde{z})/dr < 0$ at $z = H_d$.

3.2 Case B: f_{rad} is not considered and $\Omega < \Omega_K$

In most of the previous work, the effect of the radiation force exerted by the accretion disc on the outflow/jet has not been considered, while this effect is included in this work. We leave out the radiation pressure term, and re-analyze the effective potential along the field line. The analysis carried out here is in principle inconsistent with the assumption of the radiation pressure dominated accretion discs. However, the analysis is only limited to the condition of the gas being able to leave the system, which is almost independent of the disc structure. It illustrates the role of the radiation pressure in launching the outflow from the surface of the disc. The effective potential along the field line threading the accretion disc with angular velocity Ω at radius R_i can be written in dimensionless form,

$$\tilde{\Psi}_{\text{eff}}(r, \tilde{z}) = \frac{\Psi_{\text{eff}}(R, z)}{R_i^2 \Omega_K^2} = -\frac{1}{(r^2 + \tilde{z}^2)^{1/2}} - \frac{1}{2}\tilde{\Omega}^2 r^2, \quad (19)$$

where $r = R/R_i$, $\tilde{z} = z/R_i$, and, the term due to the radiation force in Equation (11) is omitted. Differentiating Equation (19), the condition for the cold gas being able to leave the disc surface is available,

$$\left. \frac{d\tilde{\Psi}_{\text{eff}}(r, \tilde{z})}{dr} \right|_{r=1, \tilde{z}=\tilde{H}_d} = \frac{r + \tilde{H}_d\kappa_0}{(1 + \tilde{H}_d^2)^{3/2}} - \tilde{\Omega}^2 \leq 0, \quad (20)$$

and we derive the lower limit on the angular velocity of the disc as

$$\tilde{\Omega} \geq \frac{(1 + \tilde{H}_d\kappa_0)^{1/2}}{(1 + \tilde{H}_d^2)^{3/4}}. \quad (21)$$

The constraint of the magnetic field strength is available,

$$\beta \leq \frac{\kappa_0}{2\tilde{H}_d} [(1 + \tilde{H}_d^2)^{3/2} - 1 - \tilde{H}_d\kappa_0], \quad (22)$$

by substituting Equation (7) into Equation (21). It is found that the critical angular velocity of the disc, above which the cold gas can be launched from the disc surface, should be greater than the Keplerian value when κ_0 is sufficiently large (see Equation 20), if the role of the radiation force on the outflow is not considered. In the case of the radiation force being properly considered, we find that the critical angular velocity of the disc is always lower than the Keplerian value (see Equation 15). It implies that the radiation force can help for launching the gas from the disc surface. We note that $d\tilde{\Psi}_{\text{eff}}(r, \tilde{z})/dr = 0$ when $\tilde{H}_d = 0$ from Equation (20). As discussed above, the second derivative of the effective potential $d^2\tilde{\Psi}_{\text{eff}}/dr^2 < 0$ at $r = 1$ and $\tilde{H}_d = 0$ is required for the cold gas being able to leave. The last term in the first derivative of the effective potential (Equation 12) is left out when the role of the radiation force on the outflow is not considered. This term remains constant along the field line, and the second derivative of the effective potential has the same form as Equation (17). Thus, our analysis without considering radiation pressure can also reproduce the same result in Blandford & Payne (1982) when $\tilde{H}_d \rightarrow 0$.

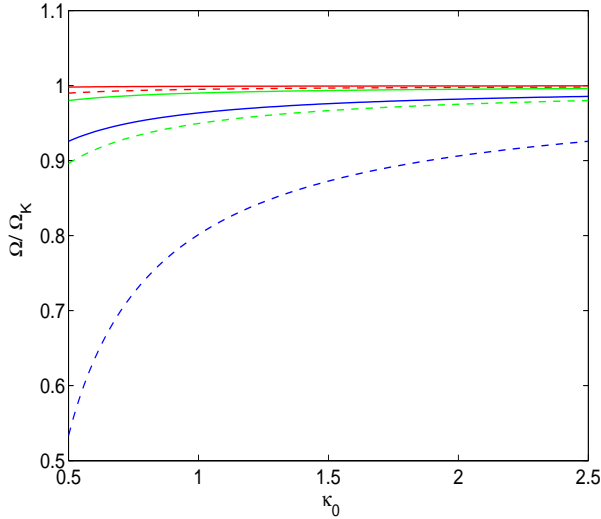


Figure 1. The angular velocity of the accretion disc as functions of β and κ_0 . The solid lines represent the results with $\beta = 0.1$, while the dashed lines are for $\beta = 0.5$. The color lines correspond the results with different values of the disc scale height: $\tilde{H}_d = 0.01$ (red), 0.1 (green), and 0.5 (blue).

4 RESULTS

As discussed in Section 2, the angular velocity of the gas in the accretion disc is dependent on the magnetic field strength β and the inclination of the field line κ_0 at the disc surface. We plot the angular velocities of the accretion disc as functions of β and κ_0 with different values of \tilde{H}_d in Figure 1. It is found that the angular velocity $\tilde{\Omega}$ increases with field line inclination κ_0 at the disc surface. For the fixed value of κ_0 , the angular velocity $\tilde{\Omega}$ increases with magnetic field strength β .

The launch of the cold gas in the disc is governed by the effective potential barrier, and the cold gas can be launched from the disc surface along the field line if the angular velocity of the gas in the disc is larger than a critical value (see Equation 15), which is plotted in Figure 2. The critical angular velocity $\tilde{\Omega}_{\text{crit}}$ decreases with increasing disc thickness \tilde{H}_d . As $\tilde{\Omega}$ is a function of β , κ_0 and \tilde{H}_d , the conditions of the cold gas can be launched from the disc surface are available as functions of κ_0 and β with given \tilde{H}_d (see Figure 3). There are upper limits on the magnetic field strength, which increase with the field inclination κ_0 and disc thickness \tilde{H}_d . For comparison, we also plot the results without considering the effect of radiation pressure from the disc in the same figure. We find more strict constraints on the magnetic field strength. The cold gas can be launched from the disc surface only if the field line is bent close to the disc surface.

5 DISCUSSION

We investigate the launch of the gas from the disc surface by the field lines threading a radiation pressure-dominated accretion disc, in which the effect of the radiation pressure from the accretion disc is considered. The launch of the outflow is sensitive to the rotational angular velocity of the gas in the disc, which is determined by the balance between the gravity of the black hole and the magnetic force. The angular velocity of the disc is a function of the field line inclination κ_0 at the disc surface and β (the ratio of the magnetic pressure to the radiation pressure in the disc), if the relative disc

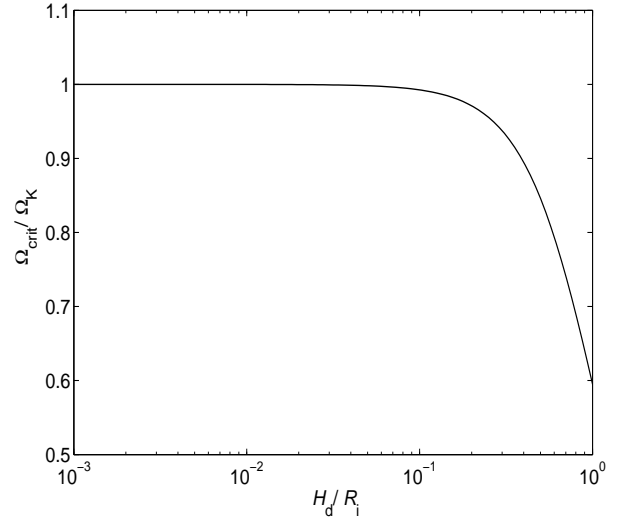


Figure 2. The condition of the cold gas can be launched from the disc surface (see Equation 15).

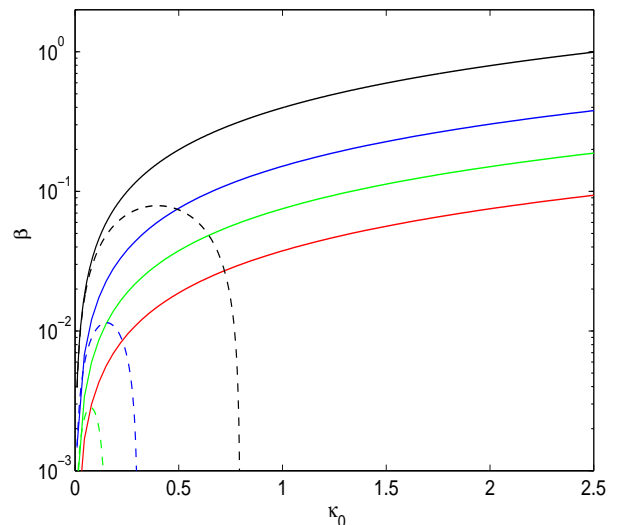


Figure 3. The solid lines represent the conditions of the cold gas can be launched from the disc surface as functions of κ_0 and β (see Equation 16), while the dashed lines are the results calculated without considering the effect of radiation pressure on the launch of the outflow/jet (see the text in Section 2.2). The colored lines are for the different disc thickness, $\tilde{H}_d = 0.05$ (red), 0.1 (green), 0.2 (blue), and 0.5 (black).

thickness \tilde{H}_d is specified (see Figure 1). It is not surprising that the angular velocity of the gas in the disc $\tilde{\Omega}$ decreases with increasing field strength β , if the values of all other parameters are fixed. The angular velocity $\tilde{\Omega}$ becomes smaller for the field line inclined at a smaller angle with respect to the disc surface, which is caused by a stronger magnetic force for a smaller κ_0 . We find that the angular velocity $\tilde{\Omega}$ decreases with increasing relative disc thickness \tilde{H}_d for the same values of β and κ_0 .

Similar to the discussion in Blandford & Payne (1982), we investigate the condition for the cold gas can be launched from the disc surface. In the presence of magnetic fields, the rotational velocity of the gas in the disc is sub-Keplerian, which makes the gas being more difficult to leave the disc surface than the Keplerian case (Ogilvie & Livio 1998, 2001). In this work, we include the effect

of radiation pressure in launching the outflow. We find that the cold gas can be magnetically driven from the disc surface if the angular velocity of the disc greater than a critical value $\tilde{\Omega}_{\text{crit}}$ (see Figure 2), which is a function of the disc thickness \tilde{H}_d . For the radiation pressure dominated accretion disc, the disc thickness \tilde{H}_d describes the importance of radiation pressure (see Equation 2). It is found that the critical value of $\tilde{\Omega}_{\text{crit}}$ decreases with increasing \tilde{H}_d , which indicates that the force exerted by the radiation from the disc indeed helps launching the outflow. The angular velocity of the gas in the disc is determined by the field strength and the inclination of the field line at the disc surface, and therefore the condition of the cold gas can be launched becomes a function of κ_0 and β (see Figure 3). For the given magnetic field line inclination κ_0 , the cold gas can be driven from the disc surface only if the field strength is lower than a certain value (see Equation 16). This is because a higher β leads to a lower angular velocity $\tilde{\Omega}$ for a fixed value of κ_0 . It is found that the launch of the cold outflow is suppressed if the magnetic field is too strong, which is due to the decrease of $\tilde{\Omega}$ with increasing β . For a relatively thick disc, the upper limit on the field strength could be high because the cold flow can be launched from the disc surface with a relatively low $\tilde{\Omega}$ with the help of the radiation force. This implies a more strict constraint on the maximal jet power can be extracted from a radiation pressure dominated accretion disc than that derived conventionally on the equipartition assumption.

In Figure 3, we also plot the results without considering the effect of the radiation pressure exerted by the accretion disc, i.e., the radiation pressure term is left out in the effective potential, in order to explore the role of the radiation pressure in launching the outflow. It is found that the cold gas can be launched from the disc surface only if κ_0 is small, i.e., the angle of the field line inclined with respect to the disc surface is small, if the radiation pressure term is not included. This implies that the role of the radiation pressure in launching an outflow is important even for thin accretion discs. The analyses in this work are carried out on the assumption of a radiation pressure dominated accretion disc, which is justified in the inner region of the accretion disc if the accretion rate is not very low (see, e.g., Laor & Netzer 1989). The calculations are done only for the cold gas driven from the disc surface, because the outflow can be efficiently driven from the place near the disc surface where the magnetic pressure is dominant over the gas pressure. The structure of the disc in the presence of a magnetic field is complicated, which should be considered by solving the differential equations governing the vertical structure of the disc and its magnetic field consistently. Such calculations without considering the effect of radiation force have already been given in the previous works (Ogilvie & Livio 1998, 2001). The similar investigations incorporated with the effect of radiation force are beyond the scope of this paper, which will be reported in our future work.

In most of the MHD simulations, the accretion flows have relative large thickness, and the gas is launched from the magnetic pressure dominated region near the disc surface (e.g., Koide, Shibata, & Kudoh 1999; De Villiers & Hawley 2003; Mościbrodzka & Proga 2009; McKinney, Tchekhovskoy, & Blandford 2012). Their the rotational velocities deviate from the Keplerian value mainly due to the magnetic force and gas pressure gradient in the radial direction (e.g., Hawley 2000; Proga & Begelman 2003). Our present analysis on the gas launched from the disc surface describes the situation more akin to the numerical simulations than that in Blandford & Payne (1982), which is valid only for the gas launched from the midplane of a Keplerian disc. The radiation of the accretion flows are calculated in some previous works based on the

structure given by MHD simulations, which are used to explain the observations (e.g., Moscibrodzka et al. 2007; Mościbrodzka et al. 2009). However, the radiation from the accretion flows has not been considered in these MHD simulations. The role of the radiation pressure on the magnetically outflows has been explored in a few MHD simulations (Proga 2000, 2003), but limited to the Keplerian disc case. The recent radiation-magnetohydrodynamic simulations on the accretion discs and outflows around black holes show that the radiation force helps launch outflows from luminous accretion discs (Takeuchi, Ohsuga, & Mineshige 2010; Ohsuga & Mineshige 2011), which is qualitatively consistent with our analytic results.

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